Final Technical Report

USGS Agreement G12AC20416
9/1/2012 – 8/31/2016

Cascadia Earthquake Early Warning Ground Motion Simulations and Evaluations

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Prepared by P. Bodin: January, 2016

Abstract

We have generated a suite of simulations of megathrust earthquake ground motions as they would be recorded at seismic and geodetic stations within Cascadia. The time series simulate ground motions expected for an M9 Cascadia earthquake, at frequencies from DC to 0.25 hz (Delorey et al., 2011). The ground motions were generated in cooperation with other ShakeAlert-related groups; Art Frankel's USGS group and the NSF-funded M9 project, whose goal is to forecast ground motions for hazard maps. The algorithms for producing the simulations have been adopted for our project to inform Cascadian megathrust Earthquake Early Warning. Figure 1 shows an example of synthetics and resultant shaking intensities from a smaller offshore M8.

Investigations

This project was one part of a considerably larger effort with the goal of implementing a prototype earthquake early warning system for the entire US west coast. The efforts funded by this grant complement those for grants from the Gordon and Betty Moore Foundation (GBMF) to the University of Washington and our partners (CalTech, UC Berkeley, and the USGS). The overall effort initiated by the GBMF extends the CISN ShakeAlert system not only throughout California, but also includes Oregon and Washington. It is expected that this working prototype will be operated by the USGS to provide public warnings about imminent earthquake-caused shaking. Moreover, in Cascadia the GBMF prototype will expand on the ShakeAlert system by incorporating high-sample-rate GPS geodetic observations to resolve permanent ground deformation associated with fault slip quickly, and to use these near-real-time estimates of fault slip in very quickly to better characterize the hazard from a rupture in progress.

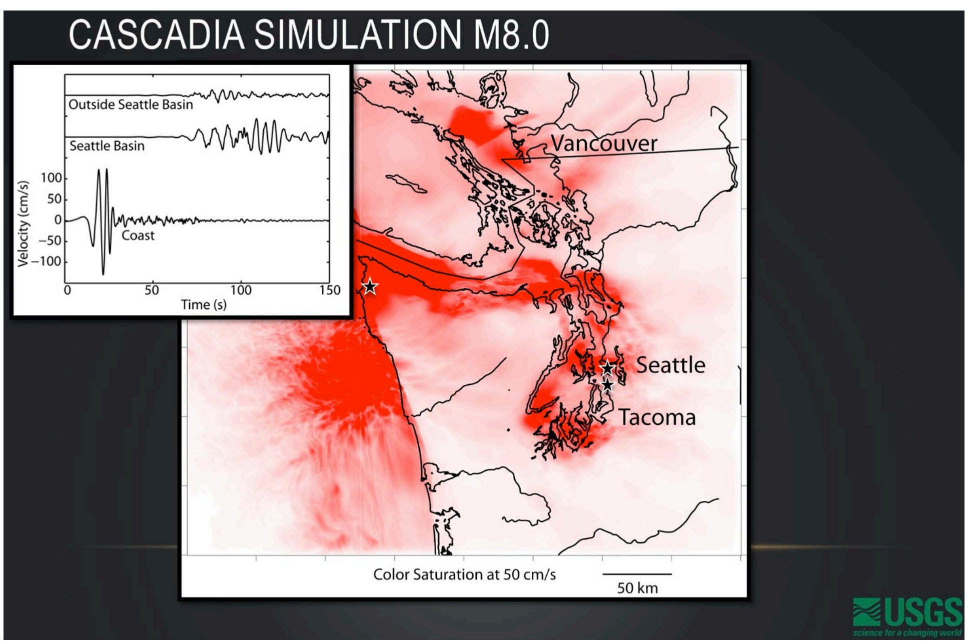

Figure 1. Example of < 0.25 Hz ground motions from a simulated M8 rupture offshore from the Olympic Peninsula (courtesy Andrew Delorey). The seismograms were produced with the finite difference code we propose to adapt for our study. Shown are ground motions from one site on the coast and two urban sites in the Puget Sound. Saturation of red shading corresponds to peak ground motion amplitudes. The earthquake source that produced these ground motions (not shown) is a simple rectangular rupture with two regions of relatively high slip offshore

Specifically this project recognizes that, particularly in Cascadia, a dearth of actual ground motion recordings of large earthquakes necessitates the production of realistic and suitable simulated ground motions to develop and test early warning methods and systems. We set out to construct and execute simulations of ground motions for a large rupture of the Cascadia megathrust fault zone. Our initial models, building on work by Art Frankel and Andrew Delorey, produced satisfactory results for low frequency motions, including permanent "static" offsets due to elastic ground deformation. They also illustrated the important modulation by crustal structure, and especially the amplification of deep sedimentary basins filled with relatively slow materials, on the expected ground motions. These propagation-related processes complicate the effects of variable (and partially unknown) fundamental source properties of rupture orientation, kinematics and directivity, stress drop and slip distribution.

We also seek simulations for a variety of smaller ruptures of crustal and intra-slab faults to develop and test the implementation of early warning for these types of Cascadian earthquakes. The hazard from these earthquakes is generally expected to be lower than that from megathrust earthquakes, to be more distributed throughout the region, and to permit only much shorter warning times to populated areas. For this reason, although they are the strong focus of EEW efforts in California, they are in some sense a secondary priority for us in Cascadia compared to great megathrust earthquakes.

Simulations of Cascadian earthquakes must therefore have a number of requirements to be useful in EEW system development and testing.
• They must provide realistic permanent ground offset ("near field terms"), in terms of sense and magnitude of offset, for simulations at seismic/geodetic monitoring sites.
• They must provide realistic impacts on the seismic wavefield due to propagation through complex crustal structures such as deep sedimentary basins. These depend not only on how well the earthquake source is characterized, but also the characteristics (and impacts) of the shaking at sites in the region.
• At the same time, they must provide realistic levels of high-frequency shaking for early phase arrivals, because these are the signals that existing ShakeAlert algorithms measure to produce warnings.
• They must be produced for sites of the regional seismic and geodetic network stations. They should reflect the characteristics of the monitoring network.
-and-
• They must have a logical "playback" system that mimics to the greatest extent possible the actual and/or expected data acquisition/processing system.
Not all of these points were clear at the outset of this project. Our understanding of them and their implications is one important outcome of the research to date.

Our overall approach was to separate the synthetic ground motion calculations into two components. The long-period wavefield (frequencies < ~1 Hz) and the quasi-static (permanent offsets) have been to date generated with 3D finite difference algorithm of Art Frankel. The higher frequencies have been generated using a stochastic ground motion approach. The two frequency bands are then merged to form single wide-band seismograms. Recently we have been experimenting with generating complete synthetics for smaller ruptures using f-k synthetics (“fk3.2”, Zhu and Rivera, 2002). These synthetics are not as accurate as the fully 3D finite difference simulations, but they are much less expensive to compute so we can produce useful simulations for a number of scenarios.

A number of students and others worked for and benefitted this project. As our understanding of the necessary steps and complexities of realistic and useful seismic synthetics grew, we involved students and staff with particular knowledge and skills. The initial work on this project was undertaken using the M9 Cascadia megathrust earthquake simulations of Art Frankel to get an intuition for the general character of ground motions such a large earthquake would generate. The simulations included propagation through 3D structure that embodied a model of sedimentary basins (i.e., the Seattle Basin, Tacoma Basin, Everett Basin, etc.). This work was performed by UW graduate student Trevor Thomas. After Trevor was awarded an MS, he decided to take a break from academics and earn a higher wage than graduate student support provides by working in the private sector.

UW student Jiangang Han was supported with the goal of refining and improving the propagation effects caused by heterogeneous 3D structure. Han has generated noise-correlation Green’s functions to more accurately delineate basins and their effects on the wavefield of offshore earthquakes. This involves generating Green’s functions from continuous observations of the offshore OBS stations of the NSF-funded Cascadia initiative and coastal stations of the PNSN and TA networks.

UW students Mika Usher and Justin Sweet also worked on this project. Their work focused on more practical aspects of putting synthetic data into the functioning test ShakeAlert system at the UW. Their efforts to put seismic data generated from both Frankel’s and Zhu & Rivera’s methods into the ShakeAlert system at UW and test the triggering of the system revealed that more “realistic” seismic noise seems to be necessary in order to successfully trigger the ShakeAlert system from synthetic data.

Moreover, the test system was enhanced to ingest recorded network seismic data, as well as synthetics. The students implemented the testing of the ShakeAlert on actual PNSN seismic data streams in an off-line mode.

In conjunction, PNSN staffer Victor Kress installed the various test ShakeAlert systems in coordination with our colleagues in California, who produced the seismic early warning algorithm we initially focussed on—ElarmS. We extended the system to include GPS data with GBMF-funded post-doc Brendan Crowell. The geodetic algorithms Brendan is implementing (called G-FAST) has used the same synthetics being developed with support from this project to develop and test the system capabilities.

At the conclusion of this project, a full USGS-operated ShakeAlert processing and notification system has been installed at the UW. This system is operating in test mode as a west-coast-wide system (*i.e.,* integrating messages from both California centers as well as from the PNW) and uses both ElarmS and OnSite seismic algorithms. Another, off-line system is testing the G-FAST geodetic algorithms in real-time mode, with offline testing being carried out using synthetic seismograms on a development system. Moreover, a full test suite of data from about 50 Cascadia earthquakes has been delivered to the “Testing & Certification Platform” group at CalTech—which is the official ShakeAlert test facility. UW/PNSN is working closely with the USGS ShakeAlert testing & certification group to provide a complete suite of synthetic ground motions for system testing and verification.

Evaluation of ElarmS and G-FAST performance in Cascadia
With the synthetics in hand, we also developed a way to locally test Earthquake Early Warning algorithms with them. Thus our test system was developed to “play back” the synthetic data at a real-time rate as input to the warning algorithms. The first step in this process was to install and configure the most appropriate early warning algorithm, ElarmS. We then developed tests of its performance within the PNSN network (Figure 2).

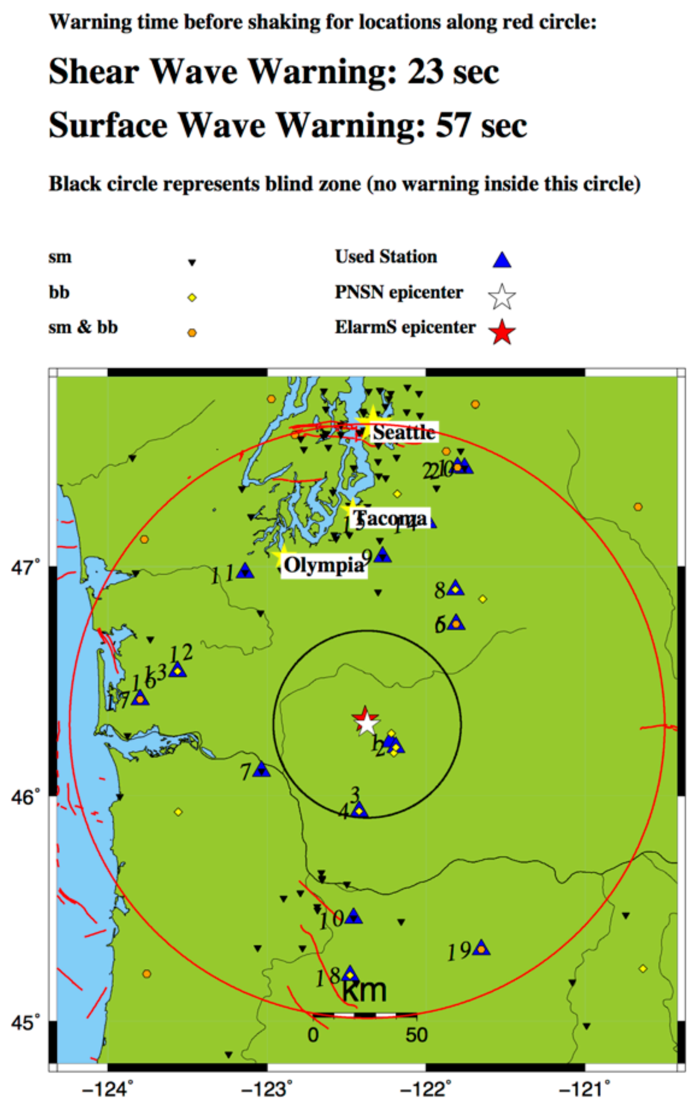

Figure 2. Example of the evaluation of an event detection history for ElarmS. The small (M3.6) earthquake’s epicenter is the white star. Blue triangles are seismic stations that detected and provided triggers to the algorithm, and the adjacent number is the order in which the triggers were reported to ElarmS. Red star is the ElarmS epicenter estimate. Initial warning was sent when seismic waves were at about the black circle.

Although this testing system has now been superseded by the ShakeAlert testing and certification platform (which it influenced and to which it contributed) this test system was fundamental to the development and testing of our algorithms in the “early days” of ShakeAlert development.

Figure 3 shows an example of scenario ground motions computed for a coastal site that hosts a real-time GPS monitoring instrument.

Figure 4 shows the results of numerous fake-quake simulations of earthquake ground motions passed through the G-FAST GPS-based EEW system. This figure illustrates the usefulness of the ground motion simulations in predicting performance of the warning system.

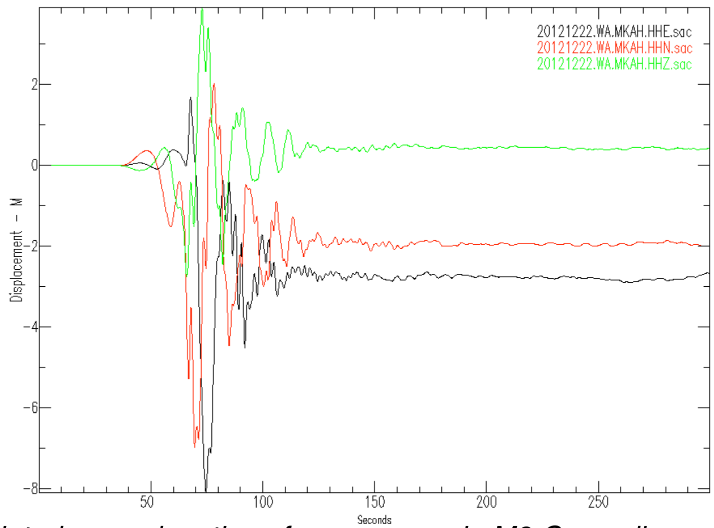

Figure 3. Simulated ground motions from a scenario M9 Cascadia megathrust earthquake computed for GPS station MKAH on the northwesternmost coast of Washington. Similar synthetic signals were generated from numerous regional earthquakes and used to test the EEW algorithm being developed at the UW.

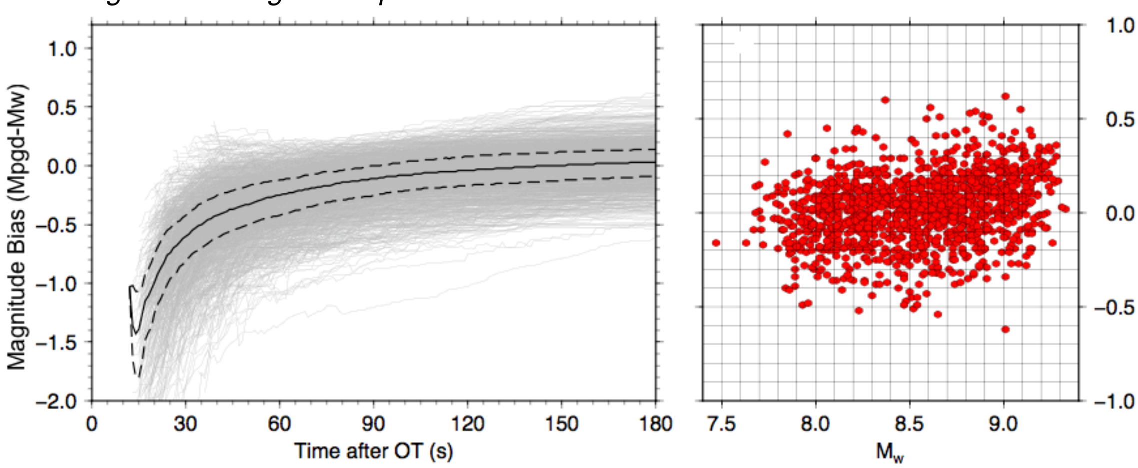

Figure 4. Magnitude Bias as a function of time (left side) after the rupture initiation time (OT) for Peak Ground Displacement (PGD) estimates determined from simulated ground motions from 100s of Cascadia megathrust earthquakes, between Mw 7.5 and 9.2, as observed by the current GPS network. The solid line is the average, and dashed lines are +/- one standard deviation of the realizations. Right side shows a point cloud of the final bias (once motion has stopped).

Bibliography

No journal articles were produced directly from this study.